Slip Performance of Galvanized Plates

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Project Sponsor: American Institute of Steel Construction, Research Council on Structural Connections

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Presentation Outline

- Background Information
  - Brief History of Changes in Slip Coefficient Provisions
  - Parameters Affecting Slip Performance of Galvanized Connections
- Development of Test Program
- Results of Slip Tests on Galvanized Connections
- Outline of Study on Effect of Zinc Creep on Bolt Pretension Force

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Background

- Hot-dip galvanizing is an economical and durable corrosion protection system.
- While methods for applying zinc coatings to iron date back to the 1700 and 1800's, the behavior of modernized galvanized connections have generally not been thoroughly studied. More specifically, limited data is available on the proper slip coefficient that should be used.

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Brief History of Slip Coefficients in RCSC and AISC

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Background – Slip Coefficients

- **AISC 1962, 1969 and RCSC 1962, 1966, 1974** No distinction among various surfaces for slip critical (friction) connections. SC = 0.35 based on mill scale.

- **AISC 1978, RCSC 1978** There were nine different classes, A thru I, depending on steel type and surface treatment and coating. Mill scale was Class A with SC = 0.33, blast cleaned carbon low alloy steel, Class B, with SC = 0.49. Hot dipped galvanized and roughened was Class D with SC = 0.40.

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Background – Slip Coefficients

- **AISC 1st Ed. LRFD, RCSC 1985** UT research showed that generic paints could not be lumped into specific categories as done in the 1978 Specifications. The Specification committees established three general classes:
  – Class A: mill Scale (SC= 0.33)
  – Class B: blasted (SC = 0.50)
  – Class C: hot-dipped galvanized and Roughened (SC=0.40).
- Paints could fall into any of these categories. The specific SC of the paint could be determined based on the Appendix A test method.

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Background – Slip Coefficients

- **AISC ASD 1989** Adopted Classes A, B and C as in the 1985 LRFD and RCSC Specifications.
- **AISC-LRFD 2nd Ed (1993) and RCSC 1988** No change from 1985/1989.
- **RCSC 1994** The SC for Class C, hot-dipped galvanized and roughened, was reduced from 0.40 to 0.35 based on the data in the 2nd Ed of the Guide (Kulak et al, 1987). The other two classes were unchanged.

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Background – Slip Coefficients

- **AISC-LRFD 3rd Ed (2000), RCSC 2000** AISC changed Class C to SC = 0.35 to be consistent with RCSC.
- **RCSC 2004, RCSC 2009 (the most recent)** No change.
- **2005 combined LRFD and ASD (13th Ed Manual)** Simplified the classes by combining former Classes A and C to just Class A, mill scale and roughened hot-dipped galvanized, with SC = 0.35.
- **2010 combined LRFD and ASD** Changed the Class A slip coefficient from 0.35 to 0.30 based on the latest Grondin data base for mill scale slip coefficients. So the SC for hot-dipped galvanized and roughened has been also reduced to 0.30.

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Early Tests on Slip Coefficients for Galvanized Steel

Background – Early Tests (<1977) As Galvanized - unroughened

Current provisions for slip performance of galvanized specimens are based on limited data that is not reflective of current galvanizing processes.

	No. of Tests	Slip Coefficient	C.O.V.
Brookhart (1966)	10	0.228	0.1
Dusel (1977)	4	0.428	0.097
Kennedy and Sanderson (1968)	18	0.150	0.185
Munse and Birkemoe (1969)	5	0.185	0.112
Steinhart and Mohler (1959)	8	0.151	0.144

Grondin, Gilbert Yves, Ming Jin, and Georg Josi. *Slip Critical Bolted Connections: A Reliability Analysis for Design at the Ultimate Limit State*. Department of Civil & Environmental Engineering, University of Alberta, 2007.

Discussion with Birkemoe – Low values likely due to paraffin oil added in quenching to give shiny surface.

Background – Surface Roughening

Early tests done on galvanized plates showed roughening improved the slip performance.

Surface Treatment	Slip Coefficient	Standard Deviation
As Received	0.21	0.08
Acetone Cleaned	0.32	0.03
Weathered	0.20	0.06
Wire-brushed	0.37	0.01
Sand-blasted	0.44	0.02
Shot-blasted	0.37	0.10

Kulak, G. L., J. W. Fisher, and J. H. Struik. "Guide to design criteria for bolted and riveted joints, 1987." American Institute of Steel Construction, Chicago, Il.

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Background – Surface Roughening

- This trend is based on a limited number of tests, and may not be representative of typical performance.
- The necessary roughening required to recognize a benefit is not explicitly specified.
- Sand-blasting or shot-blasting can produce a prescribed roughness, but the process is expensive and rarely used.
- Wire-brushing is much more common, but it is difficult to achieve a specified roughness.

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Background – Surface Roughening

- Current RCSC specifications require roughening of any galvanized surface used in slip-critical connections, but the roughening process is imprecise.

(c) *Galvanized Faying Surfaces*: *Galvanized faying surfaces* shall first be hot dip galvanized in accordance with the requirements of ASTM A123 and subsequently roughened by means of hand wire brushing. Power wire brushing is not permitted. When prepared by roughening, the *galvanized faying surface* is designated as Class C for design.

- Roughened galvanized surfaces are currently assigned a slip coefficient of 0.35 in the RCSC specification, but are grouped with clean mill scale in the AISC provisions and have a slip coefficient of 0.3.

Research Council on Structural Connections. "Specification for Structural Joints Using ASTM A325 or A490 Bolts, 2009." American Institute of Steel Construction, Chicago, Il.

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Background – Modern Galvanizing Compared with Processes 30-40 Years Ago

- Current galvanizing practices are more controlled and can produce improved consistency in coatings.
- Modern zinc baths feature increased use of alloying metals to improve adhesion of zinc, control of coatings with reactive steels, and improve aesthetic appearance of the coatings.
- The effect of these changes on slip performance of galvanized pieces has undergone little investigation.

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Objectives and Variables Considered in Current Study

Research Objectives

- Project aims to increase the experimental database of slip performance of modern galvanized pieces.
  - Determine the slip strength of untreated galvanized pieces
  - Investigate the effect of different galvanizers, steel chemistry and other variables on the slip behavior of galvanized plates
  - Evaluate the effectiveness of roughening galvanized surfaces, and, if needed, recommend a more precise procedure for roughening
- Examine the effect of zinc creep on the loss of preload in fully tightened bolts

Variables Investigated

1) Coating Thickness
2) Steel Chemistry (2 different steels)
3) Pickling Acid
4) Variation Among Galvanizers
5) Bath Consistency
6) Surface Roughening

We will first focus on “as-galvanized” behavior with no roughening

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1) Thickness of Zinc Coating

- Coating thickness has been previously observed to have an inverse relationship with slip coefficient.
- Galvanized coating thickness is dependent on many factors, including time in zinc bath, steel chemistry, and the size of the galvanized piece.
- To improve the ability to vary the coating thickness, a “reactive” heat of steel was ordered. Reactive steels achieve higher coating thicknesses with increased immersion times in the molten zinc bath. Based upon the initial test results, a “non-reactive” steel was added to the test program.

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1) Thickness of Zinc Coating

- Steels with a high percentage of silicon (>0.22%) or high percentages of phosphorous (>0.04%) are considered reactive steels.
- ASTM standards prohibit phosphorous levels above 0.04%, but allow up to 0.4% silicon. Most modern steel produced falls well below this maximum.
- A heat of steel with 0.28% silicon content was purchased for use as the reactive steel, and a heat of steel with 0.18% silicon content was used as a point of comparison.

	Grade	% Carbon	% Phosph.	% Silicon	% Copper	%Nickel	% Tin	% Alum
High Silicon Steel	A36	0.190	0.015	0.280	0.230	0.090	0.000	0.000
Low Silicon Steel	A36/A572 Gr 50	0.180	0.011	0.180	0.230	0.090	0.011	0.002

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1) Thickness of Zinc Coating

- Steels with different silicon content were selected for the primary purpose of achieving variations in the coating thickness.
- The results will provide an indication of the impact of the coating thickness on the slip performance as well as the loss of pretension force as a function of creep in the galvanizing.

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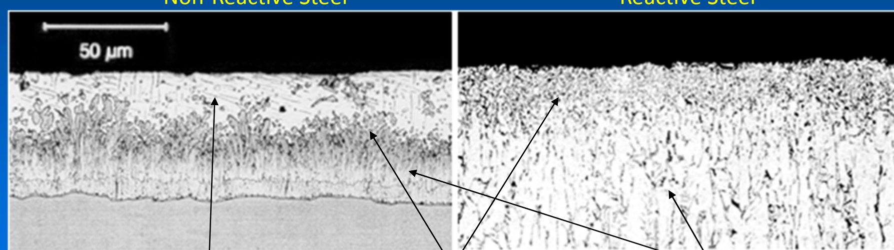
2) Steel Chemistry

- While both reactive and non-reactive steels were used to enable control of the coating thickness, the steel chemistry can also result in a change of the physical structure of the coating.

Non-Reactive Steel Reactive Steel



Eta Layer (100% Zinc, 70 DPN Hardness)

Zeta Layer (94% Zinc, 6% Iron, 179 DPN Hardness)

Delta Layer (90% Zinc, 10% Iron, 244 DPN Hardness)

http://www.galvanizeit.org/designing-for-hot-dip-galvanizing/design-fabrication/steel-chemistry-surface-condition

DPN – Diamond Pyramid Hardness

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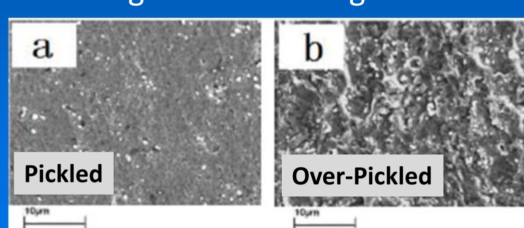
3) Pickling Acid

- Galvanized pieces must be cleaned prior to dipping in the zinc bath.
- This is done by immersion in a pickling bath, either sulfuric acid or hydrochloric acid.
- Sulfuric acid can also corrode the base metal during this pickling, resulting in a pitted surface, which could produce a rougher zinc coating.



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Guan, et al. "Effect of pickling on plating porosity and related electrochemical test," 2012, Surface Engineering. Vol. 28 No. 6

4) Variation Among Galvanizers

- Specifications allow galvanizers significant freedom in how the galvanizing process is carried out.
- The alloying metals placed in the zinc bath to control zinc coating varies among galvanizers.
- Galvanizers can air cool material after dipping, or water quench (dipping in a water bath or sprayed with water)

To ensure breadth of data, four Galvanizers were selected (pickling acid: 2 sulferic and 2 hydrochloric). The selected galvanizers provided variation in pickling acids, bath chemistries, and cooling procedures.

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5) Bath Consistency

- In addition to the alloys intentionally added by galvanizers, dipped pieces often deposit trace amounts of component metals in the zinc bath.
- Zinc is also consumed by the galvanizing process and must be replaced regularly.
- Therefore, bath chemistry of a single galvanizer can vary over time.
- To investigate the effect of this change, each galvanizer was visited at two dates several months apart.

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Preparation of Test Specimens

- Drilling (Hirschfeld) and cutting of plates (UT Austin)

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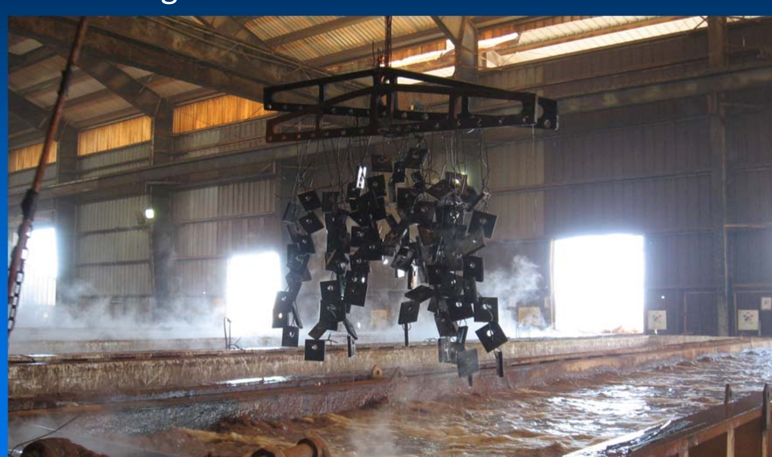
Preparation of Test Specimens

- Galvanizing of Plates



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Preparation of Test Specimens

- Local touch-up of galvanized plates

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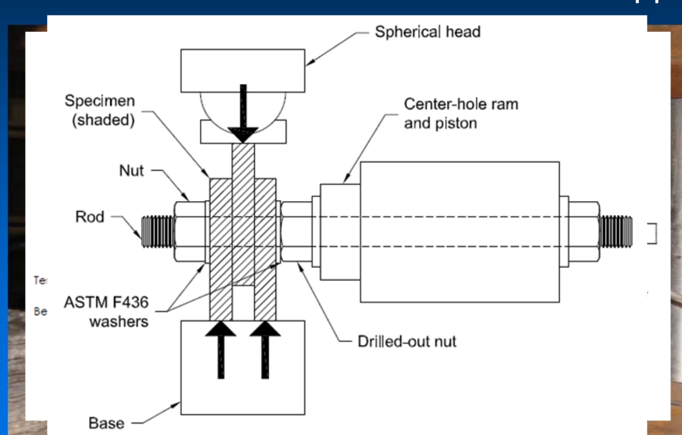
Test Setup and Procedure

- Tests conducted in accordance with RCSC - App. A



RCSC Figure A-3 (Recreated) for Compression Slip Test Setup

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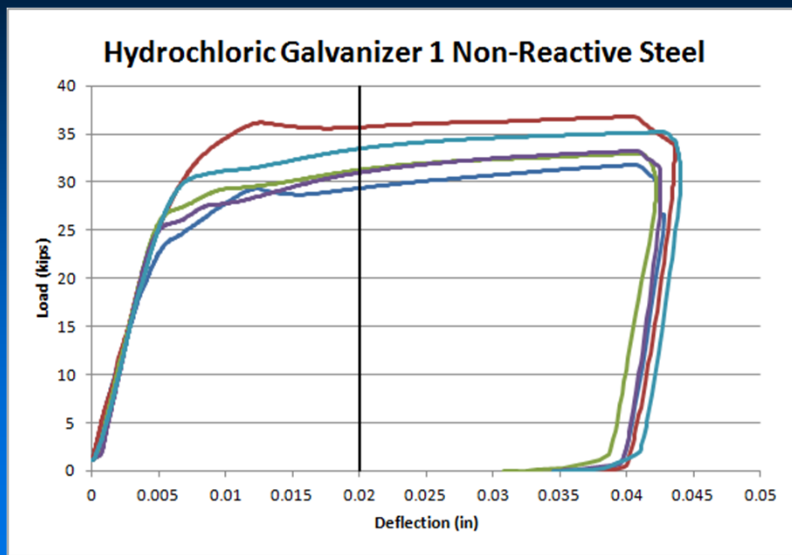
Test Setup and Procedure



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Slip Test Results

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Initial Results (Unroughened)

- Compared with previous slip studies, modern galvanizing produces coatings with much higher slip coefficients.

	Thickness	Slip Coefficient	St Dev
Ungalvanized Reactive	0.0	0.27	0.022
Ungalvanized Non-Reactive	0.0	0.36	0.024
Sulf 1 Reactive Std	2.5	0.47	0.044
Sulf 1 Reactive Thick	15.8	0.44	0.024
Sulf 1 Non-Reactive Std	3.1	0.29	0.017
Sulf 1 Non-Reactive Thick	3.9	0.26	0.009
Hydro 1 Reactive Std	7.3	0.37	0.035
Hydro 1 Reactive Thick	21.1	0.36	0.049
Hydro 1 Non-Reactive Std	5.0	0.34	0.029
Hydro 1 Non-Reactive Thick	6.4	0.33	0.027
Sulf 2 Reactive Std	5.9	0.61	0.100
Sulf 2 Reactive Thick	11.1	0.46	0.057
Hydro 2 Reactive Std	1.9	0.51	0.053
Hydro 2 Reactive Thick	6.1	0.50	0.081

Tabulated slip coefficients represent a five-test average

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Thickness of Zinc Coating (Reactive Steel)

- Coating thickness of reactive steel was approximately linearly related to dip time. Non-reactive steel showed minimal thickness variation. (3.9 mils is minimum thickness)

	Dip Time (min:sec)	Thickness (mils)
Sulf 1 Thin	5:40	6.2
Sulf 1 Thick	10:40	10.4
Hydro 1 Thin	7:00	7.3
Hydro 1 Thick	20:50	21.1
Sulf 2 Thin	5:00	5.9
Sulf 2 Thick	10:00	11.1
Hydro 2 Thin	1:30	1.9
Hydro 2 Thick	5:20	6.1

The galvanizers were asked to dip the steel long enough to achieve the standard coating – designated at “Thin” in table

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Thickness of Zinc Coating (Reactive Steel)

- In general, coating thickness did not have a significant and consistent impact on the measured slip coefficient.

	Thickness	Slip Coefficient	St Dev
Sulf 1 Std	2.5	0.47	0.044
Sulf 1 Std 2	6.2	0.50	0.065
Sulf 1 Thick	10.4	0.40	0.015
Sulf 1 Thick 2	15.8	0.44	0.024
Hydro 1 Std	7.3	0.37	0.035
Hydro 1 Std 2	7.3	0.40	0.082
Hydro 1 Thick	11.1	0.43	0.039
Hydro 1 Thick 2	21.1	0.36	0.049
Sulf 2 Std	5.9	0.61	0.100
Sulf 2 Thick	11.1	0.46	0.057
Hydro 2 Std	1.9	0.51	0.053
Hydro 2 Thick	6.1	0.50	0.081

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Steel Chemistry

- Reactive steel resulted in thicker, dull, zinc coatings.

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Steel Chemistry

- The different coating structure produced by reactive steels led to higher slip coefficients.

	Thickness	Slip Coefficient	St Dev
Sulf 1 Reactive	2.5	0.47	0.044
Sulf 1 Non-Reactive	3.1	0.29	0.017
Hydro 1 Reactive	7.3	0.40	0.082
Hydro 1 Non-Reactive	5.0	0.34	0.029

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Pickling Acid

- The use of a sulfuric pickling acid resulted in a higher average slip coefficient, but this is less significant than other variations between galvanizers.

		Thickness	Slip Coefficient	St Dev
Sulfuric	Galvanizer 1 Std	2.5	0.47	0.044
	Galvanizer 2 Std	5.9	0.61	0.100
	Galvanizer 1 Thick	15.8	0.44	0.024
	Galvanizer 2 Thick	11.1	0.46	0.057
Hydrochloric	Galvanizer 1 Std	7.3	0.37	0.035
	Galvanizer 2 Std	1.9	0.51	0.053
	Galvanizer 1 Thick	21.1	0.36	0.049
	Galvanizer 2 Thick	6.1	0.50	0.081

Reactive Steel - Similar trends with Non-reactive steel

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Bath Consistency

- Variations in bath consistency over time did not have a significant effect on slip performance.

	Thickness	Slip Coefficient	St Dev
Sulfuric 1 Std (1st Trip)	2.5	0.47	0.044
Sulfuric 1 Std (2nd Trip)	6.2	0.50	0.065
Sulfuric 1 Thick (1st Trip)	15.8	0.44	0.024
Sulfuric 1 Thick (2nd Trip)	10.4	0.40	0.015
Hydrochloric 1 Std (1st Trip)	7.3	0.37	0.035
Hydrochloric 1 Std (2nd Trip)	7.3	0.40	0.082
Hydrochloric 1 Thick (1st Trip)	21.1	0.36	0.049
Hydrochloric 1 Thick (2nd Trip)	11.1	0.43	0.039

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6) Surface Roughening – Wire Brush

To limit variations in the achieved roughening during tests, a prescribed roughening process was used:

- 10 lb applied force
- 6 cycles of 2" strokes.

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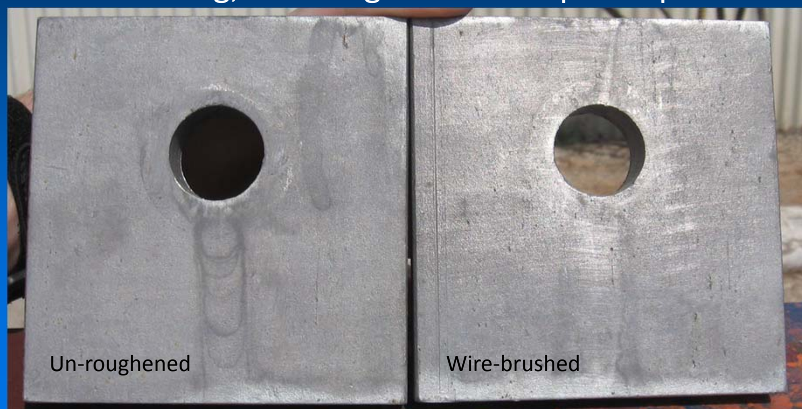
6) Surface Roughening – Wire Brush

- Galvanized specimens were not heavily altered by wire-brushing; brushing seemed to polish plates.



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6) Surface Roughening – Wire Brush

- Wire-brushing had no significant effect on slip coefficient of tested specimens.

	Thickness	Slip Coefficient	St Dev
Sulf 1 Reactive	6.2	0.50	0.065
Sulf 1 Reactive Wire	6.3	0.46	0.057
Hydro 1 Reactive	11.1	0.43	0.039
Hydro 1 Reactive Wire	9.6	0.45	0.043
Hydro 1 Non-Reactive	6.4	0.33	0.027
Hydro 1 Non-Reactive Wire	6.4	0.32	0.016

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6) Surface Roughening - Sanding

- Sandpaper is not currently approved as a roughening device, but sandpaper produced more visible roughening in reactive heat of steel.

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6) Surface Roughening - Sanding

- Sandpaper roughening had less effect on pure zinc layer of non-reactive steel, seemed to polish surface.

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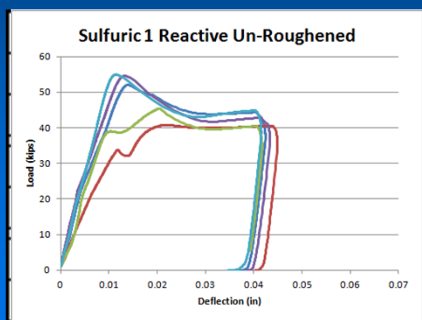
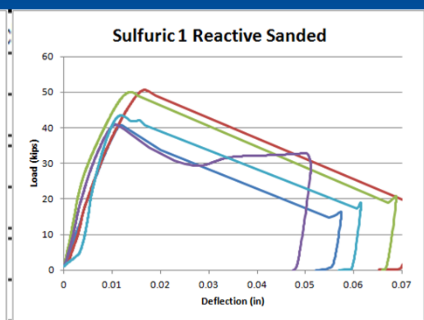
Surface Roughening - Sanded

- Despite visible roughening, sandpaper did not increase slip coefficient of galvanized plates.
- Sand paper did make failure more brittle.





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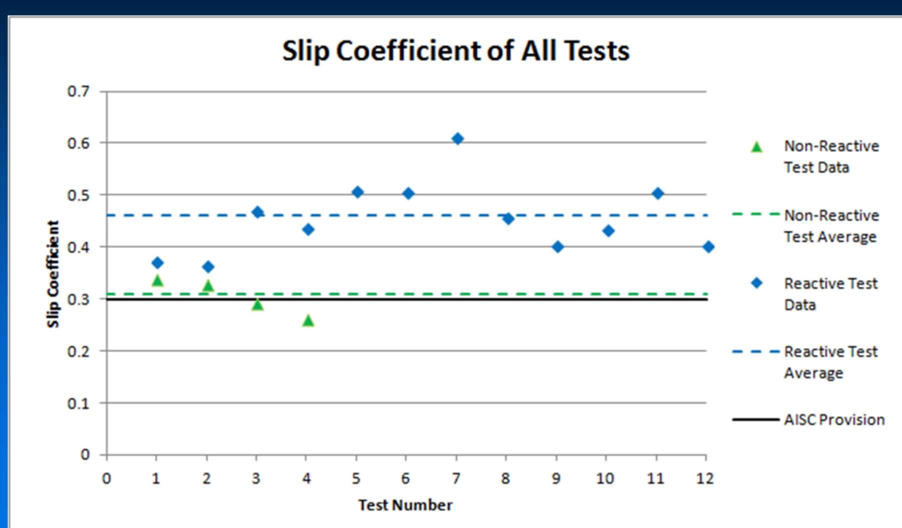
Summary of Tests to Date - Unroughened



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Summary of Tests to Date

- Modern unroughened galvanized pieces have significantly higher slip coefficients than historically used.
- Variations in coating thickness did not have a consistent or significant impact on the measured slip resistance.
- Reactive steels produced dull gray, zinc-iron surface, improved slip performance noticeably. (avg. coeff. of 0.46 vs 0.31 for non-reactive steels). It is not the intention of the researchers to include this effect in slip coefficients recommended for design.

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Summary of Tests to Date

- Bath chemistry and galvanizing process can vary between galvanizers, produce significantly different slip coefficients, however all galvanizers produced coefficients higher than historically assumed.
- Changes in bath chemistry over time had little effect on the slip coefficient of galvanized pieces.
- Surface roughening did not improve slip performance.
- The roughening procedures often reduced the measured slip resistance **and should probably therefore be removed.**

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Compression Creep of Galvanized Coatings

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Creep of Galvanized Connections

- The zinc coating of galvanized plates will creep under sustained loading, potentially reducing the clamping force in a pre-tensioned connection.
- The magnitude of this loss of clamping force, and what variables affect this loss have not been well studied.
- Test program will examine effect of creep in hardware, effect of coating thickness, and effect of physical structure of coating.

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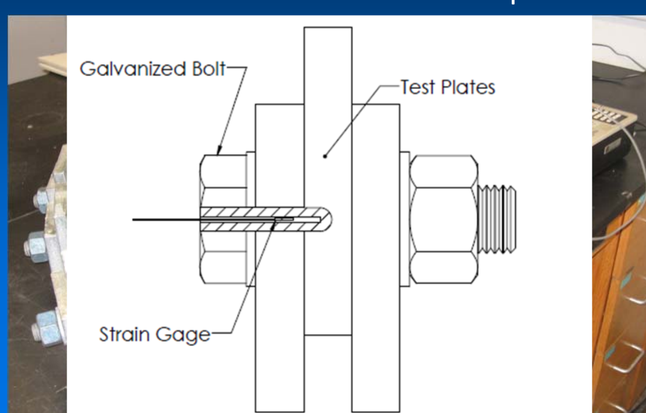
Creep of Galvanized Connections

Test Matrix: (Bolts provided by Lohr Fasteners)

Ungalvanized Bolts and Plates (Control)
Galvanized Bolts and Ungalvanized Plates
Galvanized Bolts and Non-Reactive Galvanized Plates
Galvanized Bolts and Reactive Galvanized Plates
Galvanized Bolts and Reactive Thick Galvanized Plates

Creep of Galvanized Connections

Gaged bolts are installed in connections and axial force over time is monitored to determine the loss in preload.



Future Work

- Second trip to the final two galvanizers will be taken to complete test matrix. Although the proposal called for 60-100 slip tests, the research team will have conducted 170 total tests. The last set of tests will allow the researchers to make conclusions on:
  - Pickling acid (sulferic versus hydrocholoric)
  - Impact of steel chemistry (reactive versus non-reactive)
  - Significance of change in bath chemistry over time
  - Impact of surface roughening (requirement for wire brushing should likely be removed from RCSC specification).
- Test effect of creep on bolt preload

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Acknowledgements

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- Madden Galvanizing and David Jaye
- Sabre Galvanizing and Carmen Benfield
- Southwest Galvanizing and Joe Zarate

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Thank – You!

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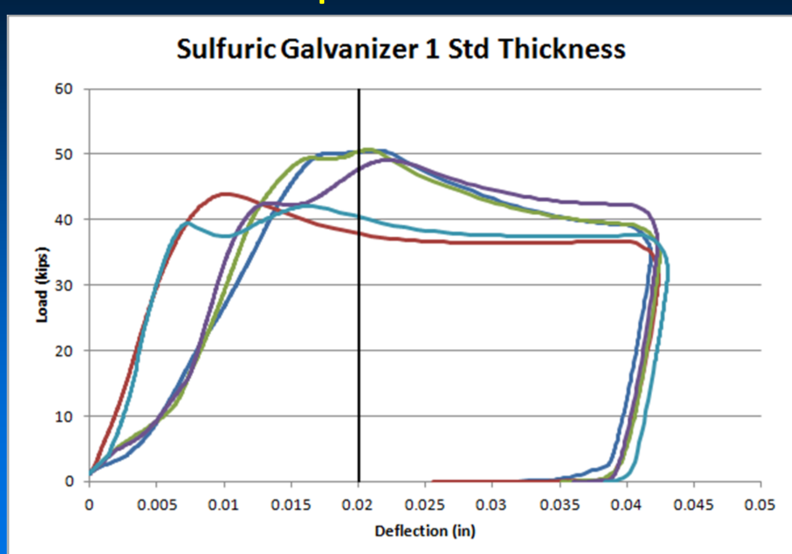
Test Setup and Procedure



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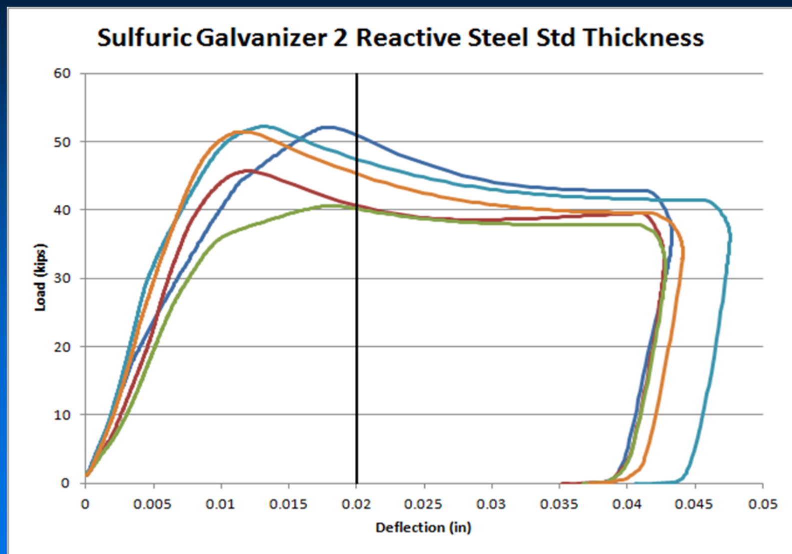
Test Setup and Procedure



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